Chapter 3
THE ACCOUNT OF WORLD TRADE CENTER 2

3.1 8:46:30 A.M. EDT

The nature of the events leading to the collapse of World Trade Center (WTC) 2 had a number of important features distinct from those of WTC 1. Those contrasts led to a larger overall fraction of the occupants surviving despite the building collapsing in a shorter period. As was the case with WTC 1, what follows is the result of an extensive, state-of-the-art reconstruction of the events that accompanied and followed the aircraft impact. Numerous facts and data were obtained, then combined with validated computer modeling to produce an account that is believed to be close to what actually occurred. The reader should again keep in mind that the building and the records kept within it were destroyed and the remains of the towers were disposed of before this Investigation began. As a result, there are some facts that could not be discerned, and there are uncertainties in this accounting. Nonetheless, the National Institute of Standards and Technology (NIST) was able to gather sufficient evidence and documentation to conduct a full investigation upon which to reach firm findings and recommendations. The reconstruction effort, the uncertainties, the assumptions made, and the testing of these assumptions are documented in Part II of this report.

The ordeal for the occupants of WTC 2 began at the same time as it did for those in WTC 1, when American Airlines (AA) Flight 11 struck WTC 1 at 8:46 a.m. Nearly all of the roughly 8,600 people in WTC 2 were well aware that something serious had occurred in the other tower. Half the people heard the terrible sound of the aircraft hitting WTC 1, just a few hundred feet away. One-fifth of the people saw the flames, smoke, or the debris ejected from the south side of WTC 1, over 10 percent felt WTC 2 moving, and another fifth in WTC 2 were quickly alerted to the seriousness of what had happened by co-workers, phone calls, or the morning news. Over half believed they were personally at risk.

Many began talking to each other, gathering personal items, and helping others. Fortunately, they began to get out of the building. Within 5 min, half the people had left their floor, and that fraction grew rapidly. About one-sixth used the elevators, with more of these people starting on the higher floors. The remainder divided themselves evenly among the three stairways. NIST estimated that approximately 3,000 people escaped because of the actions they took in the 16 min following the aircraft impact on WTC 1, especially their use of the elevators.

At 9:00 a.m. came the first building-wide public address system announcement that there was a fire in WTC 1, that WTC 2 was secure, and that people should return to their offices. This added confusion to an already tense situation, a situation that became even more turbulent when at 9:02 a.m., a contradictory announcement said that people may wish to start an orderly evacuation if conditions on their floor warranted.

3.2 9:02:59 A.M. EDT

Sixteen and a half minutes after the first impact, five hijackers flew United Airlines (UA) Flight 175, with 9 crew and 51 passengers, into WTC 2 at about 540 mph, about 100 mph faster than AA Flight 11 (Figure 3–1). UA 175 was also a Boeing 767-200ER and had also left Boston, bound for Los Angeles. It flew into WTC 2 carrying about 9,100 gal (62,000 lb) of jet fuel, evenly distributed between the inboard portions of the left and right wing tanks. The cargo bay held about 9 tons of luggage, mail, electrical equipment, and food. Combining this with the combustible cabin materials and luggage, the plane brought about 14 tons of solid combustibles into the tower with it.

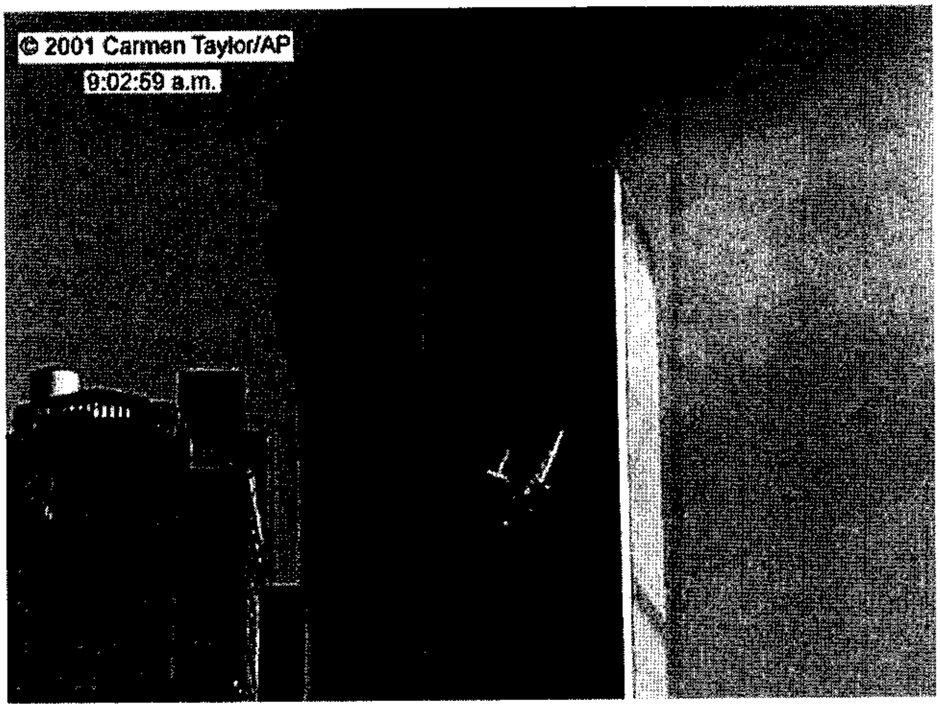


Figure 3–1. Imminent impact of United Airlines Flight 175 with WTC 2.

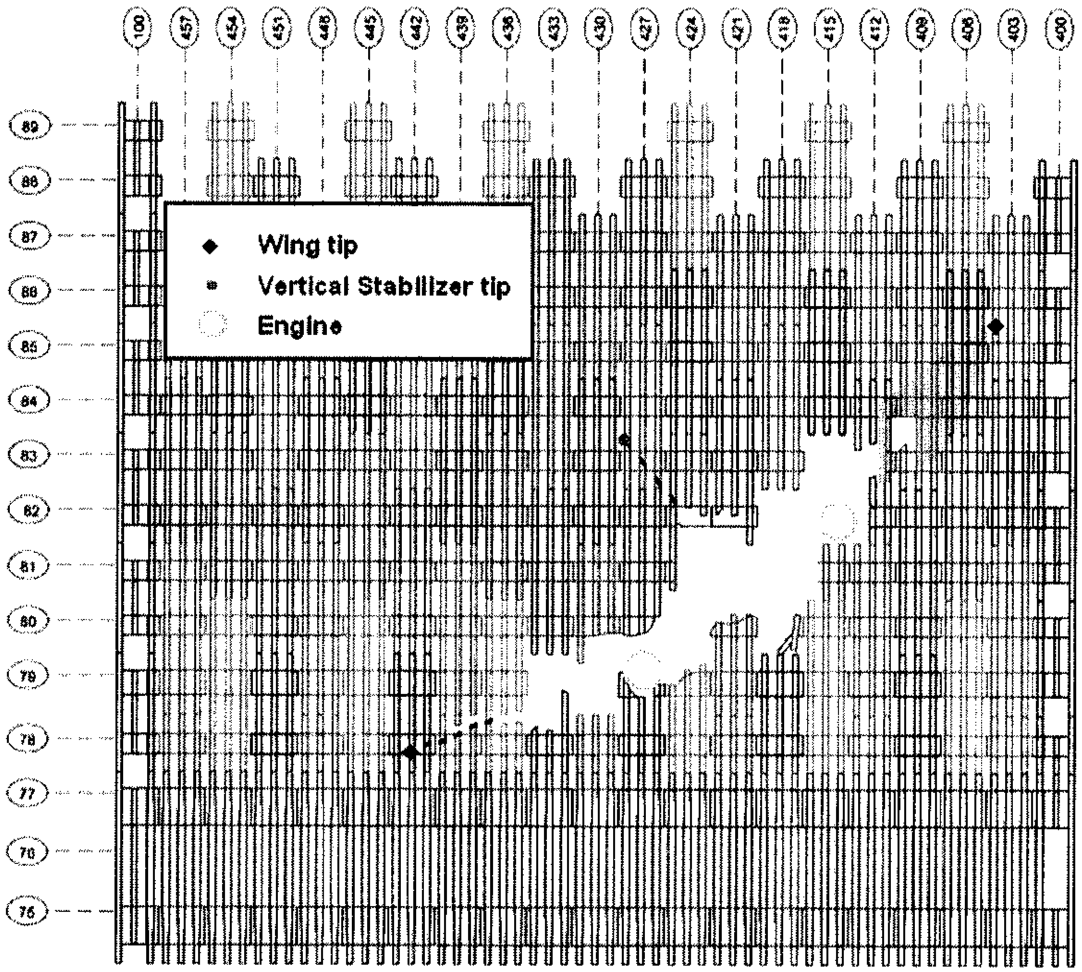
3.3 THE IMMEDIATE DAMAGE

The aircraft completely disappeared into the building in a fifth of a second. In response to the force of the collision, the top of the tower swayed 27 in. to the north, taking 2.6 s to reach the maximum displacement. UA Flight 175 was heading approximately 15 degrees east of Plan North[7] when it hit the south face of WTC 2 about 23 ft east of the center. The off-center impact twisted the upper part of the tower in a counterclockwise movement. The building vibrated in the north-south direction, along with a twisting motion, with the amplitude decreasing steadily with each oscillation.

The center of the nose of the plane struck at the 81st floor slab. The plane was banked 38 degrees to the left (right wing upward) and was heading slightly (6 degrees) downward from the horizontal. Since the

[7] Plan North was approximately 29 degrees clockwise from True North.

bank angle was steeper than that of AA Flight 11, this entry wound stretched over nine floors, from 77 to 85, rather than eight in WTC 1 (Figure 3–2). The occupancy of those floors is shown in Table 3–1.



Damage in shaded area cannot be accurately determined.

Figure 3–2. South face damage of WTC 2 with key aircraft component locations marked.

Table 3–1. Tenants on impact floors in WTC 2.

Floors	Tenant	Business
85	Harris Beach	Legal
84	Eurobrokers	Brokerage
83	Mitsui; IQ	Banking; Financial Software
79 through 82	Fuji Bank	Banking
77 and 78	Baseline	Investment Services

The bulk of the impact damage was confined to six floors. Figure 3–3 shows the combined damage. Floors 77, 84, and 85 were struck only by the outer extent of the wings. Empty of fuel, the light framing

and aluminum sheet of the wing did little damage to the building structure or the SFRM on the columns and trusses on these floors. There were 433 broken windows on the north, east, and south facades.

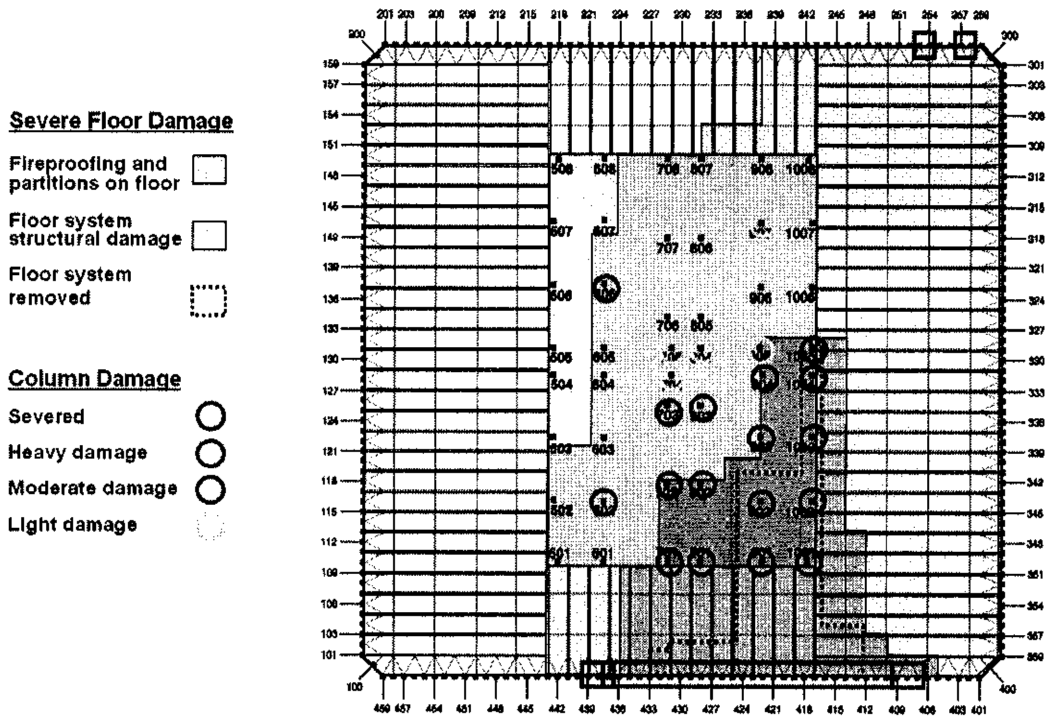


Figure 3–3. Simulation of aircraft impact damage to the 78th through 83rd floors in WTC 2.

The middle of the left wing hit the 78th floor, severing nine perimeter columns and breaking 19 windows on the south face. The SFRM was stripped from the floor trusses over the same width as the building core. The stripping of insulation from the trusses continued inward across the tenant space and about two thirds of the way into the core. There was no direct core column damage from the debris on this floor. However, the southeast corner core column was so damaged on the 80th floor that it broke at its splices on the 77th and 83rd floors.

There was heavier damage to the 79th floor. The left engine and the inboard section of the left wing shattered a 25 ft wide section of the center of the floor slab all the way to the core of the building and severed 15 perimeter columns. Reaching the building core, the debris severed nine columns, heavily damaged another, and abraded the SFRM from the eastern two thirds of the columns and trusses all the way to the north end of the core.

The damage was most severe on the 80th and 81st floors, hit directly by the fuselage. On the lower floor, a chunk of the floor slab was broken, just above the affected piece of the 79th floor. In addition, a 70 ft deep strip along the east side of the core floor was crushed. The north side floor slab sagged along its eastern end. Ten of the perimeter columns severed on the 79th floor were displaced here also. Within the building core, ten columns were severed, including many that were severed on the 79th floor. The SFRM was stripped not only from the eastern two thirds of the core structural elements, nearly to the north wall, but also from most of the trusses on the east tenant space, all the way to the north façade.

On the 81st floor, the fuselage pulverized a section of the floor 40 ft wide that extended into the southeast corner of the core. The SFRM and gypsum fire protection on the full depth of the east side of the core and in the entire east side of the tenant space was stripped. The structural damage to the core columns was limited to near the southeast corner, but as mentioned above, the impulses felt here caused damage to the key corner column all the way down to the 78th floor. The right engine passed all the way through the 81st floor, exited from the northeast corner, and damaged the roof of a building on Church Street, before coming to rest some 1,500 ft northeast of WTC 2 near the corner of Murray and Church Streets. The right landing gear assembly passed through the 81st floor at the east side of the north face and landed near the engine on the roof of a building on Park Place. (See Figure 1–1 for the street locations relative to the towers.)

The right engine hit the 82nd floor spandrels about 50 ft from the east edge of the building, crushing part of the 82nd floor slab. Along with the inboard section of the right wing, it severed eight to nine perimeter columns, including some to the east of those severed on the lower floors. The wing caused truss damage up to the southeast corner of the core and severed five columns. As on the 81st floor, the fire protection on the east side of the tenant space and the east side of the core was dislodged.

The 83rd floor caught the middle of the starboard wing. The east side floor slab appeared to be dislodged and sagged at least half of the way into the building.

The result of the core column damage was that the building core leaned slightly to the southeast above the impact zone. The tendency of the core to lean was resisted by the floors and the hat truss.

The direct impact of the aircraft was over in about 0.6 s. The structural and insulation damage, summed over all floors, was estimated to be:

- 33 exterior columns severed, 1 heavily damaged.
- 10 core columns severed, 1 heavily damaged.
- 39 of 47 core columns stripped of insulation on one or more floors.
- Insulation stripped from trusses covering 80,000 ft^2 of floor area

The tower swayed more than one foot back and forth in each direction on the impact floors, about one-third the sway under the high winds for which the building was designed. Nonetheless, just like WTC 1 across the Plaza, *WTC 2 absorbed the aircraft strike and remained standing.*

By 9:03 a.m., most of the people in WTC 2 had already left their usual work floors. Nearly 40 percent of all the occupants had left the building, (Table 3–2), and 90 percent of those who would survive had begun their evacuation. Many of those still on the east side of the impact floors were likely killed or seriously injured by the impact. The same was true for many of those on the 78th floor skylobby, who were deciding on a course of action, waiting for the express elevators to transport them to the ground floor, or attempting to return to their offices. Those on the west side of the building were less seriously affected. In calls to 9-1-1, they reported fallen ceiling tiles, collapsed walls, jet fuel, heat, smoke, and fire.

Table 3–2. Location of occupants of WTC 2.

Time	Escaped	Lobby to 76th Floor	77th to 110th Floor
8:46	0	5,700	2,900
9:03	3,200	4,800	637
9:36	6,950	1,050	619
9:59	8,000	11	619

Note: The numbers in the rows do not add to the estimated total of 8,600 occupants due to rounding in the less certain values.

This aircraft had also severed the pipes that fed the automatic sprinklers and destroyed all elevator service to the impact floors. But, unlike AA Flight 11, the off-center strike of UA Flight 175 had left one of the three stairways passable, Stairway A on the north side of the building core.

> Stairwell A remained passable because it was well west of the aircraft strike center and partially protected by elevator machinery and the long dimension of the building core.

When the aircraft struck WTC 2, emergency responders had already been dispatched to the WTC site, and the initial surge of emergency responder radio had subsided to a level approximately three times that of normal operations. However, the radio traffic volume was still at a level where approximately one-third to one-half of the radio communications was not understandable.

3.4 THE JET FUEL

Within about one half of a second, dust and debris flew out of windows on the east and north faces. Several small fireballs of atomized jet fuel burst from windows on the east face of the 81st and 82nd floors, coalescing into a single, large fireball that spanned the entire face. A tenth of a second later, fire appeared in the dust clouds ejected from the south face of the 79th, 81st, and 82nd floors. Almost simultaneously, three fireballs came from the east side of the north face. The largest came from the 80th through 82nd floors. A second, somewhat smaller one came from the same floors on the northeast corner of the building. The smallest emerged from the 79th floor. No dust or fireballs came from the west face.

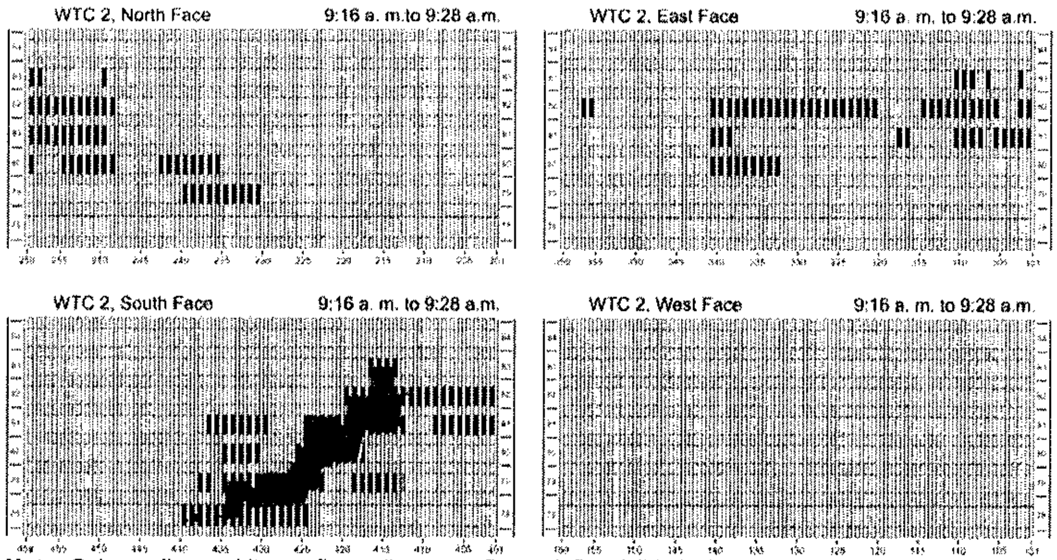
As in WTC 1, less than 15 percent of the jet fuel burned in the spray cloud inside the building. Roughly 10 percent to 25 percent was consumed in the fireballs outside the building. Thus, well over half of the jet fuel remained after the initial fireballs.

The rapid burning of the jet fuel inside the building created an overpressure that was estimated at 2 psi to 3 psi for 0.5 s to 2 s. For a window and frame of over 10 ft^2, this amounts to over 3,000 pounds of force, more than enough to break windows. Photographs of the north and east faces appeared to show hanging floor slabs where the fireballs had been ejected from the building. Based on the failure of the truss seat connections, NIST estimated that the static capacity of an undamaged floor was 4.8 psi against uplift pressure and 4.4 psi against downward pressure over the entire floor. It is not unreasonable that a combination of physical damage from the impact and overpressure from the fireballs caused the partial collapse of these floor slabs.

3.5 9:03 A.M. TO 9:36 A.M. EDT

The fireballs burned for 10 s, extending almost 200 ft out from the north, east, and south faces. Having consumed the aerosol fuel, the flames then receded.

For the next half hour, small fires were burning in and near the aircraft impact cavity on the south side of the building. There were vigorous fires on the east side of the 80th through 83rd floors (Figure 3–4), especially on the northeast end of the 81st and 82nd floors, where the aircraft had bulldozed the office desks and chairs and added its own combustibles. In addition to the ample supply of fuel, these fires had access to plenty of air, as numerous windows on the east face had been blown out by the impact or fireball. They would continue to burn as long as the building stood.



Note: Color coding—white, no fire; yellow, spot fire; red, fire visible inside; orange, external flaming.

Figure 3–4. Representation of exterior views of the fires on the four faces of WTC 2 at about 9:20 a.m.

Between 9:30 a.m. and 9:34 a.m., there were several large bursts of smoke from the 79th and 80th floors of the north face, possibly resulting from the ignition of pools of jet fuel that had settled there, or from shifting of dislodged floor slabs elsewhere.

Dire structural changes were occurring in the building interior. Core columns, including the massive southeast corner column, had been severed by the aircraft. The loads from these columns had been redistributed to other, intact core columns and to the east exterior wall. The core leaned to the south and east, restrained from further movement by the east and south walls through the floors and the hat truss.

The fires were weakening the structure in a manner different from WTC 1. First, the severed core columns in the southeast corner led to the failure of some column splices to the hat truss. Nonetheless, the hat truss continued to transfer loads from the core to the perimeter walls. Second, the overall load redistribution increased the loads on the east wall. Third, the increasing temperatures over time on the long-span floors on the east side had led to significant sagging on the 79th through 83rd floors, resulting in an inward pull force. Fourth, within 18 min of the aircraft impact, there was inward bowing of the east perimeter columns as a result of the floors sagging. As the exposure time to the high temperatures lengthened, these pull-in forces from the sagging floors increased the inward bowing of the east perimeter columns.

Meanwhile, people continued their evacuation. By 9:36 a.m., almost 7,000 of the 8,600 occupants had left the building. From the impact floors and above, 18 occupants had discovered that the hot, smoke-filled, debris-laden Stairway A was not fully blocked and had made their way to survival. It is not known how many more of the 619 other people who had been on or above the impact floors became aware of this, but none made it out of the building. There are no records of information regarding this escape route having been collected and transmitted to others who might have been able to use it.

The PAPD, NYPD, and FDNY centers were now being inundated with calls from the two buildings. In the confusion, some of the callers did not identify which building they were in. At 9:12 a.m., PAPD was notified that the WTC 2 floor warden phones were not working. Other calls alerted them to trapped and injured people. At 9:18 a.m., FDNY reported that they had a single elevator working to floor 40. A simultaneous call indicated that FDNY was relocating its command post across West Street. At 9:30 a.m., EMS set up a triage desk in the lobby of WTC 2.

3.6 9:36 A.M. TO 9:58 A.M. EDT

By 9:58 a.m., all but eleven of the occupants who had been below the impact floors had left the building and crossed the street to safety.

The fires continued to burn in the east half of the building.

At 9:55 a.m., firefighters communicated that they had reached floor 55 of WTC 2, one of the few calls for which a record survived indicating how high the responders had reached. Before WTC 2 collapsed, firefighters had reached the 78th floor by using the single functioning elevator to the 40th floor and then climbing the stairs.

The physical condition of the tower had deteriorated seriously. The inward bowing of columns on the east wall spread along the east face. The east wall lost its ability to support gravity loads, and, consequently, redistributed the loads to the weakened core through the hat truss and to the adjacent north and south walls through the spandrels. But the loads could not be supported by the weakened structure, and the entire section of the building above the impact zone began tilting as a rigid block to the east and south (Figure 3–5). Column failure continued from the east wall around the corners to the north and south faces. The top of the building continued to tilt to the east and south, as, at 9:58:59 a.m., WTC 2 began to collapse.

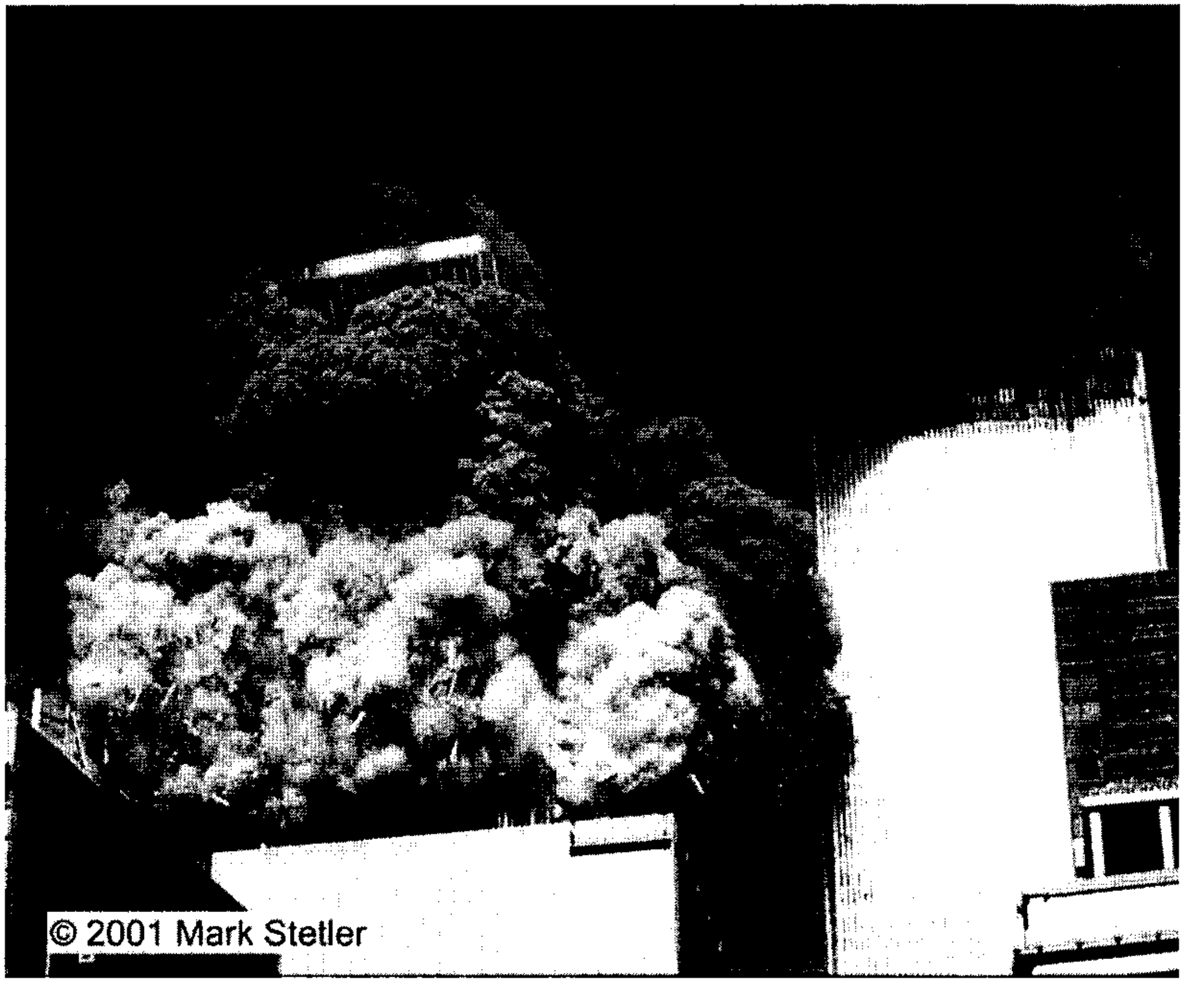


Figure 3–5. Photograph of WTC 2 tilting to the southeast at the onset of collapse.

3.7 THE OUTCOME

Seven factors led to the collapse of WTC 2:

- Direct structural damage from the aircraft impact, which included more severe damage to the core columns than in WTC 1;
- Jet fuel sprayed into the building interior, that ignited widespread fires over several floors;
- Dislodging of SFRM from structural members due to the aircraft impact and aircraft and building debris, which enabled rapid heating of the unprotected structural steel;
- Sustained fires on the east side of the tower and an ample air supply;
- Weakened core columns that increased the loads on the perimeter walls;

- Sagging of the east floors, that led to pull-in forces on the east perimeter columns; and
- Bowed east perimeter columns that had a reduced capacity to carry loads.

After the building withstood the initial aircraft damage, the timing of the collapse was largely determined by the time for the fires to weaken the perimeter columns and floors on the east and south sides of the building. That the aircraft impact damage to the core was more severe in WTC 2 than in WTC 1 contributed to the shorter time to collapse.

The loss of life in WTC 2 was significantly reduced by the prompt start of evacuation activity before the tower was hit by the aircraft. Only a quarter of those initially on or above the impact floors died when the building collapsed, as contrasted with 100 percent in WTC 1. Eighteen people on those upper floors found that one stairwell was passable in time to evacuate. Whether others found this escape route is unknown.

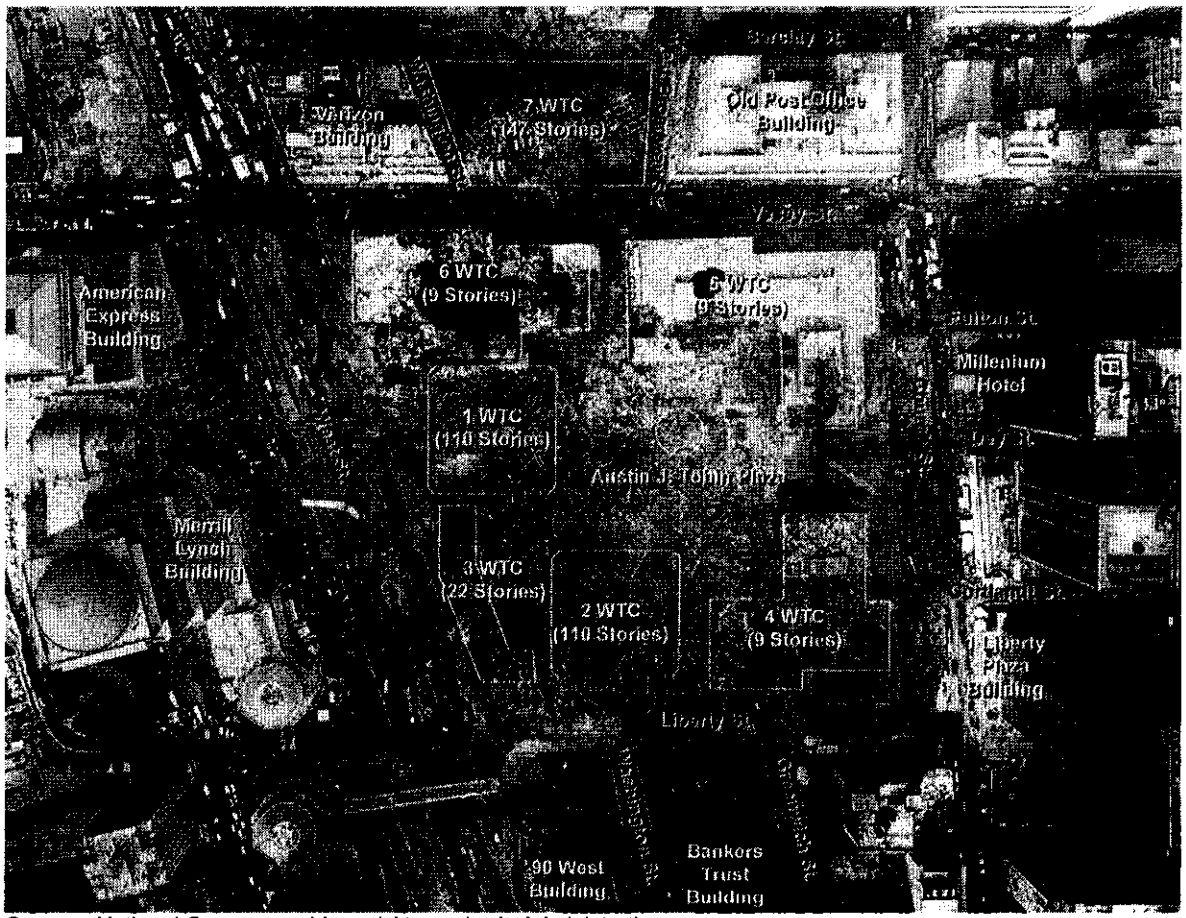
As with WTC 1, had the building been more than one-third occupied, the casualties would have been far higher as the population would have exceeded the capacity of the stairwells to evacuate them in the time available.

Of the roughly 6,000 people who started the morning below the 77th floor, all but 11 evacuated the building, indicating sufficiently efficient movement within the three stairwells within the time available.

Even more than in WTC 1, those emergency responders who entered WTC 2 and the emergency personnel who were already in the building were helpful in assisting the evacuation of those below the impact floors. However, there was insufficient time to reach any survivors on the impact floors and above. Any attempts to mitigate the fires were fruitless due to the lack of water supply and the difficulty in reaching the fire floors within the time interval before the building collapse. It is not known precisely how many emergency responders entered the building nor how many of the 421 emergency responder casualties occurred in WTC 2.

Chapter 4
THE TOLL

By sunset on September 11, 2001, all seven buildings on the World Trade Center (WTC) site lay in ruins (Figure 4–1). Table 4–1 compiles the likely locations of the decedents.



Source: National Oceanographic and Atmospheric Administration.

Figure 4–1. The WTC site on September 17, 2001.

Table 4–1. Likely locations of WTC decedents at time of impact.

Location[a]	Number	
WTC 1 Occupants (Total)		**1,462**
At or Above the Impact Floors	1,355	
Below the Impact Floors	107	
WTC 2 Occupants (Total)		**630**
At or Above the Impact Floors	619	
Below the Impact Floors	11	
Confirmed Below Impact Zone in WTC 1 or WTC 2		**30**[b]
Unknown Location Inside WTC 1 or WTC 2		**24**[c]
Emergency Responders (Total)		**421**[d]
FDNY	343	
NYPD	23	
PAPD	37	
Hospital/Paramedic	7	
Federal	2	
Volunteer Responders	9	
Bystander/Nearby Building Occupant		**18**
American Airlines Flight 11		**87**[e]
United Airlines Flight 175		**60**[e]
No Information		**17**
Total		**2,749**

a. Where possible, NIST used eyewitness accounts to place individuals. Where no specific accounts existed, NIST used employer and floor information to place individuals.
b. These individuals were typically security guards and fire safety staff who were observed performing activities below the floors of impact after the aircrafts struck.
c. These 24 individuals were largely performing maintenance, janitorial, delivery, safety, or security functions.
d. Emergency responders were defined to be people who arrived at the site from another location. Thus, security staff and Port Authority staff (different from PA Police Officers) were not defined as emergency responders.
e. Does not include the five hijackers per aircraft.

PART II: RECONSTRUCTING THE DISASTER

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Chapter 5
THE DESIGN AND CONSTRUCTION OF THE TOWERS

5.1 BUILDING AND FIRE CODES

Codes for the design, construction, operation, and maintenance of buildings are the blueprints by which a society manifests its intent to provide public safety and welfare. They incorporate the knowledge, experience, procedures and practices of the applicable engineering disciplines, the values of the contemporary society, the experiences from prior successes and failures, and knowledge of the commercial products, services, and technologies available for the tasks at hand.

In the United States, building and safety regulations of state and local jurisdictions are most frequently based on national "model" building codes (model codes). Developed under the auspices of private sector organizations in an open process, the model codes include minimum requirements for public health, safety, and welfare. The model codes are traditionally organized into volumes according to the official responsible for their enforcement and include a building code, fire code, plumbing code, electrical code, mechanical code, etc. The model codes adopt by reference voluntary consensus standards developed by a large number of private sector standards development organizations. These standards include measurement methods; calculation methods; data sets; and procedures and practices for design, construction, operation, and maintenance.

The model codes and referenced standards do not become law until they are adopted legislatively or administratively by a jurisdiction empowered to enforce regulations, for example, a state or city. These jurisdictions may modify specific provisions of the models codes and referenced standards to suit local conditions or traditional practices. Once legally adopted, the totality of the modified model codes and standards are referred to as building regulations.

Proposals to modify the model codes, offered by individuals or organizations, are discussed in open forums before being accepted or rejected by a voting process. Localities adopting model codes update their versions periodically as well, but typically not on the same schedule. To a lesser and decreasing extent, some jurisdictions have generated their own building codes to reflect specialized local conditions and preferences. The Federal government's role in determining specific codes is minimal and not mandatory (except for federally owned, leased, regulated, or financially assisted properties).

There are also key stakeholder groups that are responsible for or influence the practices used in the design, construction, operation, and maintenance of buildings in the United States through the code development process. These include organizations representing building owners and managers, real estate developers, contractors, architects, engineers, suppliers, and insurers. (Infrequently, members of the general public and building occupants participate in this process.) These groups also provide training, especially as it affects the ability to implement code provisions in practice, since lack of adequate training programs can limit the application of improved code provisions.

5.2 THE CODES AND THE TOWERS

5.2.1 The New York City Building Code

The New York City (NYC) Building Code was and is part of the Administrative Code of New York City. Until recently, the various versions of the Code were not based on any model code, but rather were written by local code development committees. However, there are many similarities between the versions of the NYC Code and the model codes of the same time, since they all reflected accepted practice.

The NYC Code has been amended from time to time by Local Laws to update safety requirements or to incorporate technological advances. These Local Laws were enacted by the New York City Council. To aid the implementation of and to clarify building code requirements, New York City issued mandatory "rules" that were typically initiated by City Government offices and issued under authority of the Building Commissioner.

At the time the WTC project began in the early 1960s, the 1938 NYC Building Code was in effect. In 1960, reflecting growing dissatisfaction with the failure of the Code to keep pace with changes that had occurred in the building industry, the Building Commissioner requested the New York Building Congress to form a working committee to study the problem. On December 6, 1968, Local Law 76 repealed the 1938 code and replaced it with the 1968 code. As is the general custom with changes to building codes, the new provisions did not apply to buildings approved under the prior code, provided they did not represent a danger to public safety and welfare, or until they underwent a major renovation or change in primary use.

The 1968 NYC Building Code also included "Reference Standards." These included standard test methods and design standards published by standards development organizations. Some of these Reference Standards included modifications to the published standards, as well as stand-alone standards developed by New York City.

Through 2002, 79 Local Laws had been adopted that modified the 1968 Building Code. The major Local Law affecting the structural design of buildings dealt with seismic provisions. Five of the Local Laws had provisions that pertained to fire protection and life safety that were of interest to the WTC Investigation:

- Local Law 5 (1973) added, among other specifications, requirements for:
  - Compartmentation (subdivision) within upper story, unsprinklered, large floor areas. Its provisions applied retroactively to existing office buildings.
  - Signs regarding the use of elevators and stairs, also retroactive.
  - A fire alarm system for buildings more than 100 ft in height.
- Local Law 55 (1976) added a requirement for inspection of all sprayed fire protection, effective immediately but not retroactive.
- Local Law 33 (1978) added a requirement for trained fire wardens on each floor.

- Local Law 86 (1979), among other provisions, required full compliance with Local Law 5 by February 7, 1988, and exempted fully sprinklered buildings from compartmentation requirements.

- Local Law 16 (1984) added requirements for sprinklers in new and existing buildings taller than 100 ft. Since Local Law 5 only required compartmentation of non-sprinklered spaces, this negated the compartmentation requirements from Local Law 5.

The World Trade Center (WTC) was located in Manhattan and would normally have been designed and constructed according to the NYC Building Code of 1938. However, the WTC was constructed by The Port Authority of New York and New Jersey (The Port Authority or PANYNJ) on land that it owned. As an interstate agency established under a clause of the United States Constitution permitting compacts between states, The Port Authority's construction projects were not required to comply with any building code. Nonetheless, The Port Authority instructed its consultants to design the two towers to comply with the 1938 NYC Code. In 1965, The Port Authority directed the architect and consulting engineers to revise their designs for the towers to comply with the second and third drafts of what would become the 1968 NYC Code. The rationale for this step was that the new Code allowed the use of advanced techniques in the design of the WTC, as well as more lenient provisions regarding exit stairs and the reduced fire ratings. To reaffirm a "long standing policy" of The Port Authority that its facilities meet or exceed NYC Building Code requirements, a formal memorandum of understanding between The Port Authority and the New York City Department of Buildings was established after the bombing in 1993.

5.2.2 Pertinent Construction Provisions

To gain perspective on the conditions under which the WTC towers were constructed, the rationale for the design, and the building structures themselves, the National Institute of Standards and Technology (NIST) and its contractors reviewed tens of thousands of pages of documents provided by The Port Authority and its contractors and consultants, Silverstein Properties and its contractors and consultants, the Fire Department of the City of New York, the NYC Police Department, the NYC Law Department, the NYC Department of Design and Construction, the NYC Department of Buildings, the NYC Office of Emergency Management, the manufacturers and fabricators of the building components, the companies that insured the WTC towers, and the building tenants.

NIST deemed it important to understand how the provisions under which the WTC was constructed and maintained compared to equivalent provisions in place elsewhere in the United States at that time. The Investigation selected three codes for comparison:

- The 1964 New York State (NYS) Building Code, which governed construction outside the New York City limits

- The 1965 Building Officials and Code Administrators (BOCA) Basic Building Code, a model building code typically adopted by local jurisdictions in the northeastern region of the United States

- The 1967 Municipal Code of Chicago, under which the Sears Tower (110 stories) and the John Hancock Center (100 stories) were built

For the most part, the provisions in the various codes were similar, if not identical, indicating that there was a common understanding of the essentials of building safety and that the codes were at similar stages of evolution:

- There were only modest differences among the codes in the provisions for gravity loads.
- All three of the contemporaneous building codes had provisions for wind loads that were less stringent than those used for the tower design.
- None of the codes had provisions for design against progressive collapse.
- For alterations or additions to a building, there were criteria to determine whether the whole building or only the alterations needed to comply with the current code requirements. The "trigger" was either the fraction of the building cost involved in the renovation or the fraction of the building dimensions. The 1968 NYC Building Code was slightly less conservative than the Chicago Code and the BOCA Code. The NYS Code required that any addition or alteration conform to the contemporary code.
- The 1968 NYC Building Code required inspection of sprayed fire protection, but did not specify if testing was required.
- Only the NYC Building Code contained provisions for bracing (lateral support to prevent buckling of columns and walls) and stresses associated with transverse deflections of structural members.

NIST examined the 2001 edition of the NYC Building Code to determine the extent to which Local Laws had modified the code provisions between the times of construction and collapse of the towers. The 2001 edition of the NYC Building Code was essentially the same as the 1968 edition, as amended by the intervening Local Laws.

5.2.3 Tenant Alteration Process

With hundreds of tenants, The Port Authority realized that many would want extensive modifications to their space, both before they moved in and during the course of their occupancy. In anticipation, The Port Authority:

- Set up a special office to review and approve plans, issue variances, and conduct inspections.
- Developed a formal tenant alteration process for any modifications to leased spaces in WTC 1 and WTC 2 to maintain structural integrity and fire safety. The *Tenant Construction Review Manual*, first issued in 1971, contained the technical criteria, standards, and review criteria for use in planning alterations (architectural, structural, mechanical, electrical, and fire protection). Alteration designs were to be completed by registered design professionals, and as-built drawings were to be submitted to The Port Authority. The 1968 NYC Building Code was referenced. The review manual was updated four times and supplemented, in 1998, by the *Architectural and Structural Design Guidelines, Specifications, and Standard Details*.

The interiors of the towers had been heavily modified over the years due to tenant turnover, same-tenant space usage changes, the addition of sprinklers, and asbestos abatement.

5.3 BUILDING DESIGN

5.3.1 Loads

The NYC Building Code specified minimum design values for both dead and live gravity loads and for lateral (wind) loads.

- Each tower was designed to support dead loads (its own weight) consistent with the provisions in the 1968 NYC Building Code. The dead loads included the weight of the structural system and loads associated with architectural, mechanical, plumbing, and electrical systems.
- Each tower was designed to support live loads (the combined weights of the people and the building contents) exceeding those specified in the 1968 NYC Building Code.
- The design wind loads used in the towers were higher than those required by the 1968 NYC Building Code and the three other codes identified earlier.

5.3.2 Aircraft Impact

The accidental 1945 collision of a B-25 aircraft with the Empire State Building sensitized designers of high-rise buildings to the potential hazards of such an event. However, building codes did not then, and do not currently, require that a building withstand the impact of a fuel-laden commercial jetliner. A Port Authority document indicated that the impact of a Boeing 707 aircraft flying at 600 mph was analyzed during the design stage of the WTC towers. However, the investigators were unable to locate any documentation of the criteria and method used in the impact analysis and were thus unable to verify the assertion that "...such collision would result in only local damage which could not cause collapse or substantial damage to the building and would not endanger the lives and safety of occupants not in the immediate area of impact."[8] Since the ability for rigorous simulation of the aircraft impact and of the ensuing fires are recent developments and since the approach to structural modeling was developed for this Investigation, the technical capability available to The Port Authority and its consultants and contractors to perform such an analysis in the 1960s would have been quite limited.

5.3.3 Construction Classification and Fire Resistance Rating

Building codes classify building constructions into different "Types" or "Classes." The Class pertinent to the WTC towers was Class 1 (fire resistive). The 1938 NYC Building Code had no subdivisions of Class 1 construction, which required a 4 hour fire resistance rating for columns and a 3 hour rating for floors. The 1968 version of the Code subdivided Class 1 for office occupancies into 1A, with requirements identical to the 1938 Class 1, and 1B. Class 1B specified a 3 hour rating for columns and

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[8] Letter with an attachment dated November 13, 2003, from John R. Dragonette (Retired Project Administrator, Physical Facilities Division, World Trade Department) to Saroj Bhol (Engineering Department, PANYNJ).

girders supporting more than one floor and a 2 hour rating for floors including beams. There were no height or area requirements that differentiated between Class 1A and Class 1B, and the towers could have been classified as either one. The Port Authority elected to provide the fire protection in the WTC towers with Class 1B standards.

Achieving a specified rating for a truss-supported floor using a sprayed fire-resistive material (SFRM) was an innovation at the time of the WTC design and construction. NIST was not able to find any evidence that there was a technical basis to relate SFRM thickness to a fire resistance rating, nor was there sufficient prior experience to establish such thickness requirements by analogy. NIST did find documentation that the Architect of Record and the Structural Engineer of Record had each written to The Port Authority, stating that the fire rating of the WTC floor system could not be determined without testing. NIST was unable to find any indication that such tests were performed nor any technical basis for the specification of the particular SFRM product selected or its application thickness.

The NYC Building Code required inspection at the time of application of the SFRM, to be conducted under the supervision of a building inspector or a licensed design professional who assumed responsibility for compliance. This inspection included verification of the thickness of the material, its density, and its adhesion, each using a specific ASTM test method. The Code contained a requirement that SFRM installed in areas where it was subject to mechanical damage be protected and maintained in a serviceable condition.

> There were no code requirements nor general practice by which sprayed fire-resistive material was to be inspected over the life of the building.

5.3.4 Compartmentation

Both the 1968 NYC Building Code and The Port Authority practice required partitions to separate tenant spaces from each other and from common spaces, such as the corridors that served the elevators, stairs, and other common spaces in the building core. These were intended to limit fire spread on a floor and to prevent the spread of a fire from one tenant space to that of another.

- The Port Authority specified partitions separating tenant spaces from exit access corridors to have a 2 hour rating. This allowed dead end hallways to extend to 100 ft (rather than 50 ft with 1 hour partitions), which permitted more flexibility in tenant layouts. Above the ceiling, penetrations for ducts or to allow for return airflow were fitted with rated fire dampers to preserve the fire rating. This 2 hour rated construction was not used in the original design, but was specified later by The Port Authority as tenant spaces were altered.

- For walls separating tenant spaces to achieve a 1 hour rating, they needed to continue through any concealed spaces below the floor and above the ceiling. The Port Authority chose to stop these demising walls at the bottom of the suspended ceiling and use 10 ft strips of 1 hour rated ceiling on either side of the partition. There was no precedent for this approach and, after a warning from the general contractor, the tenant alteration guidelines required that tenant partitions have a continuous fire barrier from top of floor to bottom of slab.

- There were no requirements in the 1968 NYC Building Code or in The Port Authority guidelines for partitions wholly within tenant spaces. As mentioned in Section 1.2.2, these

gypsum board walls generally ran from the floor slab to just above the suspended ceiling, although some extended to the slab above when the tenant desired additional sound attenuation. For these partitions to be fire rated, the ceiling would have had to be rated as well but were not required to be so.

- Enclosures for vertical shafts, including stairways and transfer corridors, elevator hoistways, and mechanical or utility shafts were required to be of 2 hour fire rated construction. These innovative walls are further described below.

There was a conflict regarding the number of partitions within a tenant space. On the one hand, the design of the WTC towers was intended to provide about 30,000 ft^2 per floor of nearly uninterrupted space and access to views of the Manhattan panorama. On the other hand, Local Law 5 dictated compartmentation into no more than 7,500 ft^2 areas for unsprinklered spaces. These areas could be increased to 15,000 ft^2 if protected by 2 hour fire resistive construction and smoke detectors. The compartmentation limit was removed when complete sprinkler protection was provided. Following a 1975 fire, The Port Authority began installing sprinklers at the time a new tenant moved in. By September 11, 2001, the installations had been completed throughout the towers, and, in general, the tenants on the impact floors had few internal partitions except for those surrounding conference rooms and executive offices.

Firestopping materials are used to fill gaps in walls and floors through which smoke and flames might pass. Such passage could negate the fire endurance value of the wall or floor. The 1968 NYC Building Code included comprehensive requirements identifying when and where firestopping was required. The 1964 New York State Building Code addressed the issue in less detail, and the Chicago Building Code had no requirements. The National Fire Protection Association (NFPA) Life Safety Code had firestopping requirements for exterior and interior partitions at floor levels, and did allow a trade-off for sprinklered concealed spaces. In the towers, unlike many buildings, the exterior wall was connected with the floors without gaps.

5.3.5 Egress Provisions

The primary egress system for the office spaces was the three stairways located in the building core. There were four main requirements for these stairways: number, width (including separate width requirements for the doors), separation of the doors to the stairways, and travel distance to the stairway doors.

The number of stairways and the width of the doors resulted from the implementation of the 1968 edition of the NYC Building Code, whose provisions were less restrictive than those in the 1938 edition. The 1968 code eliminated a fire tower (an enclosed staircase accessed through a naturally ventilated vestibule) as a required means of egress and reduced

> The NYC Building Code used the "units of exit width" method for specifying exit capacity, in which each 22 in. unit of exit width provided the capacity for 60 people. Thus each 44 in. stairwell provided for 120 people and the 56 in. stairwell provided 2½ units, or 150 people, for a total occupant load per floor of 390.

the number of required stairwells from six to three[9] and the width of the doors leading to the stairs from 44 in. to 36 in.

Of the three staircases, two (designated A and C) were 44 in. wide; stairway B was 56 in. wide. The largest occupant load in the office spaces was 365 people per floor (36,500 ft^2 on the largest floor, with 100 ft^2 per person). Neither the 1968 NYC Building Code nor any of the contemporaneous codes mandated consideration of the number of building stories in determining the number and widths of the stairwells.

For the floors classified in the office use group (all floors except the observation deck and restaurant/meeting spaces), a minimum of two stairwells would have been required to serve the occupants, each equally sized. The three modern building codes considered in this report [International Building Code (IBC) (2000), NYC Building Code (2003), and NFPA 5000 (2003)], as well as the 1968 NYC Building Code, were consistent in this requirement, each regardless of building height. However, the resulting width of these minimum requirements would differ. Two 44 in. stairwells would have satisfied IBC minimum requirements, two 65 in. stairwells would have satisfied NFPA 5000 requirements, and two 78 in. stairwells would have satisfied the 1968 and 2003 NYC Building Code requirements. Alternatively, as was built at WTC 1 and WTC 2, three stairwells of narrower construction, but equivalent or greater total required width, would also satisfy the egress requirements in the modern building codes.

The 1968 NYC Building Code contained a requirement that the stairwells be "as far apart as practicable." Since the stairwells on the impact floors of WTC 1 were substantially closer together than those on the impact floors of WTC 2, it certainly was possible to have designed a greater separation in WTC 1. Local Law 16 (1984) added a quantitative requirement that the separation between exit door openings be at least one-third of the maximum travel distance of the floor. For the WTC towers, this maximum distance was 180 ft, and the smallest separation of stairwell doors was 70 ft. The towers were consistent with this requirement.

NFPA 5000 (2003) and IBC (2000) incorporate a requirement that the separation of the stairwells be no less than one-third the overall diagonal length of the building. For the towers this length was 294 ft, and one-third was 98 ft. Thus, the stairwell separations on some floors would have been inconsistent with the later codes (with which the buildings in New York City were not required to comply).

At the top of the two towers were floors that were classified as public assembly floors: the Windows on the World restaurant complex in WTC 1 (floors 106 and 107) and the Top of the World observation deck in WTC 2 (floor 107). The design number of occupants on each of these floors was over 1,000. On September 11, 2001, there were about 188 people in the Windows on the World and few in the Top of the World since it was before the opening hour. Thus, had the stairwells remained passable through the impact region, the capacity would have been sufficient for the occupant load observed on that morning. Nonetheless, the egress requirements for assembly occupancy were more stringent than for business occupancy in both the NYC Building Code in 1968 and in 1996, when the Windows on the World re-opened after refurbishment following the 1993 bombing in the basement. NIST found documentation that, in 1996, The Port Authority created areas of refuge consistent with the provisions of the 1968 NYC

[9] See discussion of the required number of stairwells later in this section.

Building Code, but NIST was unable to find evidence indicating that the requirements for the number of exits for the evacuation of over 1,000 people from each of these floors had been considered in the design or operation of the buildings. In 1995, the NYC Department of Buildings, however, had reviewed the egress capacity from these floors and apparently concurred that the proposed remodel to these spaces would meet the intent of the NYC Building Code.

Subsequently, NIST communications in 2005 with The Port Authority and the NYC Department of Buildings identified a difference of interpretation regarding the number of exits required to serve these floors. The Port Authority stated that a fourth exit was not required since the assembly use space in question constituted less than 20 percent of the area of principal use, with principal use area defined as the entire building. The Department of Buildings stated that the 20 percent rule did not apply to assembly spaces such as restaurants and observation decks that are open to the public, and therefore exit reduction cannot be applied and a fourth exit was required.

The Department further clarified that areas of refuge and horizontal exits are not to be credited for required means of egress (unless the spaces are used non-simultaneously) and that for places of assembly, with occupant load in excess of 1,000, the floor shall have a minimum of four independent means of egress (stairs) to street. If the floor were divided into areas of refuge with rated walls, as was the case for the WTC towers, each area is to be considered an independent place of assembly that needs its own access to two means of egress (stairs) without going through another assembly space if they have an occupant load of less than 500 each (or three means of egress if the area of refuge had an occupant load between 500 and 999). Further, since the only means of egress from the roof-top deck was through the space on the observation floor, the Department clarified that occupant load from the deck would need to be added to the occupant load of the observation floor and that the travel distance from the roof deck along the connecting stairs to the required means of egress at the observation floor shall be within the maximum permitted by the NYC Building Code. The Department, however, did not raise the issue of a fourth stairwell in its December 1994 meeting with The Port Authority and when it subsequently concurred with The Port Authority's proposal to remodel the spaces.

Given the low occupancy level on September 11, 2001, NIST found that the issue of egress capacity from these places of assembly, or from elsewhere in the buildings, was not a significant factor on that day. It is conceivable that such a fourth stairwell, depending on its location and the effects of aircraft impact on its functional integrity, could have remained passable, allowing evacuation by an unknown number of additional occupants from above the floors of impact. If the buildings had been filled to their capacity with 20,000 occupants, the required fourth stairway would likely have mitigated the insufficient egress capacity for conducting a full building evacuation within the available time.

The elevator system was described in Chapter 1. These were not to be used for emergency evacuation except under the control of the fire department. Roughly 3,000 of the people who were initially at or above the impact floors in WTC 2 and were warned by the attack on WTC 1 survived, however, in large part by taking the elevators downward before the aircraft struck WTC 2.

Following the 1993 bombing, The Port Authority instituted the following changes to reduce egress time, in addition to those stairwell improvements mentioned in Section 1.1.2:

- Construction of new egress corridors, north (to Church Street and Vesey Street) and south (to Liberty Street) for faster evacuation from the Concourse (mall), and of two escalators from

the Concourse (mall), one to the plaza at WTC 5 and one up to WTC 4 and onto Church Street.

- Semiannual fire drills in conjunction with the FDNY.
- Appointment of Fire Wardens, specially trained and equipped with flashlights, whistles, and identifying hats.

Building Communications

WTC emergency procedures specified that all building-wide announcements were to be broadcast from the Fire Command Desk (FCD), located in the lobby of each WTC tower (Figure 5–1), using prepared text. A situation requiring evacuation for any reason, including fire or smoke, would have led to the following announcement, enabling a phased evacuation:

> "Your attention please. We are experiencing a smoke condition in the vicinity of your floor. Building personnel have been dispatched to the scene and the situation is being addressed. However, for precautionary reasons, we are conducting an orderly evacuation of floors _____. Please wait until we announce your floor number over the public address system. Then follow the instructions of your fire safety team. We will continue to keep you advised. We apologize for the inconvenience and we thank you for your cooperation."[10]

A Fire Command Desk (Figure 5–1) was located in the lobby of each tower. The computer screen monitored the fire alarms, smoke sensors, sprinkler water flow, elevator lobby smoke detectors, fire signal activation, air handling fans, status of elevators, and troubles with the fire systems.

The announcement to be used when a particular floor required an evacuation was:

> "Your attention please. It is now time for your floor to be evacuated. In accordance with the directions from your fire safety team, please take the exit stairs nearest to your location. We remind you that communications, emergency lighting and other essential services are in service. We will continue to keep you advised. We apologize for the inconvenience and we thank you for your cooperation."[10]

At the discretion of the Fire Safety Director, the information and instructions broadcast to the building occupants could be modified to suit the nature of the emergency.

[10] The Port Authority of New York and New Jersey. World Trade Center Emergency Procedures Manual 2001.

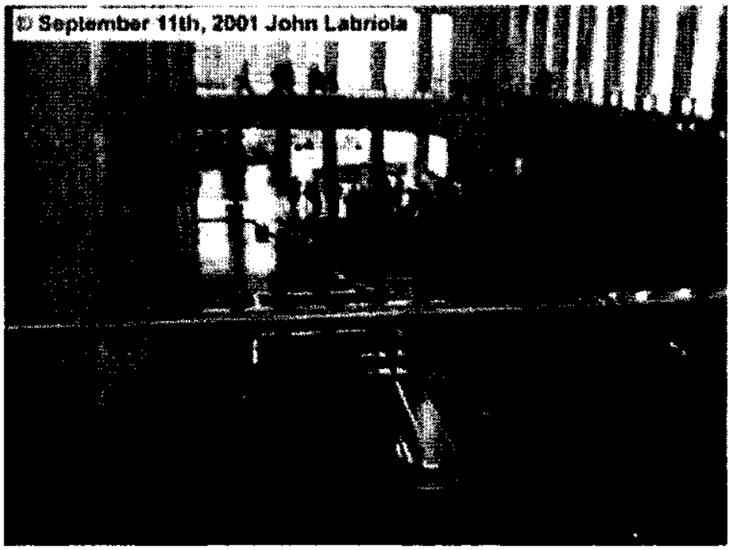


Figure 5–1. Fire Command Desk in WTC 1, as seen from a mezzanine elevator, looking west.

5.3.6 Active Fire Protection

The provision of fire safety in the WTC towers revolved around a Fire Safety Plan that provided direction for fire emergency response and was organized around a hierarchy of staff trained in its implementation. In charge in each tower was the Fire Safety Director, who oversaw emergency response until the arrival of the Fire Department of the City of New York (FDNY), gathered necessary information, and relayed it to the Fire Chief upon arrival. In an emergency, the Fire Safety Director proceeded to the FCD or the fire scene. He/she had one or more Deputy Fire Safety Directors located at the FCD and at the sky lobbies. The front line was a set of Floor Wardens and Deputy Floor Wardens who were responsible for assessing conditions and assisting the evacuation of occupants on their respective floors. The Floor Wardens had their own communications system.

Built into each tower were four resources to mitigate the effects of a fire: an alarm system to alert people to the presence of the fire, an automatic sprinkler system and a standpipe system for controlling the fire by the application of water, and a smoke venting system to improve visibility as people proceeded toward exits. The primary documentation of the design, installation, maintenance, and modification of these systems was stored on the 81st floor of WTC 1 and was lost when that building collapsed. Contractors to the Investigation Team were able to re-create descriptions of the physical systems and their capabilities from limited duplicate information provided by The Port Authority, Silverstein Properties, Inc, and contractors, consultants, and operators involved with the systems.

The original fire alarm system used the technology current at the time and was engineered exclusively for the World Trade Center towers. The 1993 bomb explosion in WTC 1 destroyed the communications to the Operations Control Center, and the alarm system was revealed to be vulnerable to a single point of failure. Repair was problematic, since spare parts for the 25-year-old system were unavailable, and the software was no longer supported. The Port Authority immediately commissioned a new state-of-the-art system for WTC 1, WTC 2, WTC 4, WTC 5, and the subterranean levels. This retrofit involved the installation of over 10,000 detectors, pull stations, and monitors; 30,000 notification devices (speakers

and strobe lights); 150 miles of conduit; and 1,000 miles of wiring. Redundant Operations Control Centers were located in the basements of both towers.

The primary monitoring and control of the fire alarm system was performed at the FCD located in the lobby of each building. The new system included:

- Numerous interconnected microprocessors located in each of the four WTC buildings.
- Smoke sensors located throughout the tenant spaces, at each elevator landing, in return air ducts, and in electrical and mechanical rooms.
- At least one manual fire alarm station installed in each story in the evacuation path.
- Emergency voice and alarm speakers for notification and communication in all areas within the buildings, designed to ensure system function in the event 50 percent of the system became inoperable.
- Automatic notification of the fire department upon fire alarm activation.
- Two-way communications stations at the remote fire panels, at the Floor Warden stations, and at the standpipes.
- A two-way telephone system for the firefighters to make announcements.
- Emergency voice and alarm communication capability, both under manual control at the FCD.
- Strobe lights to provide alarm indications for the hearing impaired.
- Water flow indicators for the fire sprinkler system, including indicators for disabled systems.

No documentation of the status of the replacement system survived the 2001 attack. However, a 2002 analysis estimated that over 80 percent of the towers had been retrofitted and that about 25 percent of the original system was still in use.

Although there were localized carbon dioxide and halon systems within the towers, the Safety Plan predominantly relied on water for containing and suppressing a fire (Figure 5–2). By September 11, 2001, automatic sprinklers had been installed throughout WTC 1 and WTC 2.[11] The New York City water distribution system supplied water to the complex from two independent connections located under Liberty Street to the south and Vesey Street to the north. Within each tower were six 5,000 gal water storage tanks, three located on the 110th floor and one each on the 20th, 41st, and 75th floors. These were filled from the domestic water supply in the building. In the event of a fire, the gravity-fed water would flow to as many of the thousands of installed sprinklers as had been activated. The WTC engineering staff would supply additional water upward from the city mains using manually

[11] The exceptions to this were the computer rooms (protected with halon and carbon dioxide systems), kitchens (protected with dry chemical and steam smothering systems), mechanical spaces on the 108th through 110th floors, and the electrical rooms throughout the buildings, for which the application of water would have been inappropriate.

started pumps located in the towers; the FDNY could augment the supply using fire department connections and truck-based pumps. While there were redundant vertical supply pipes, there was only a single connection to the array of sprinklers on any given floor.

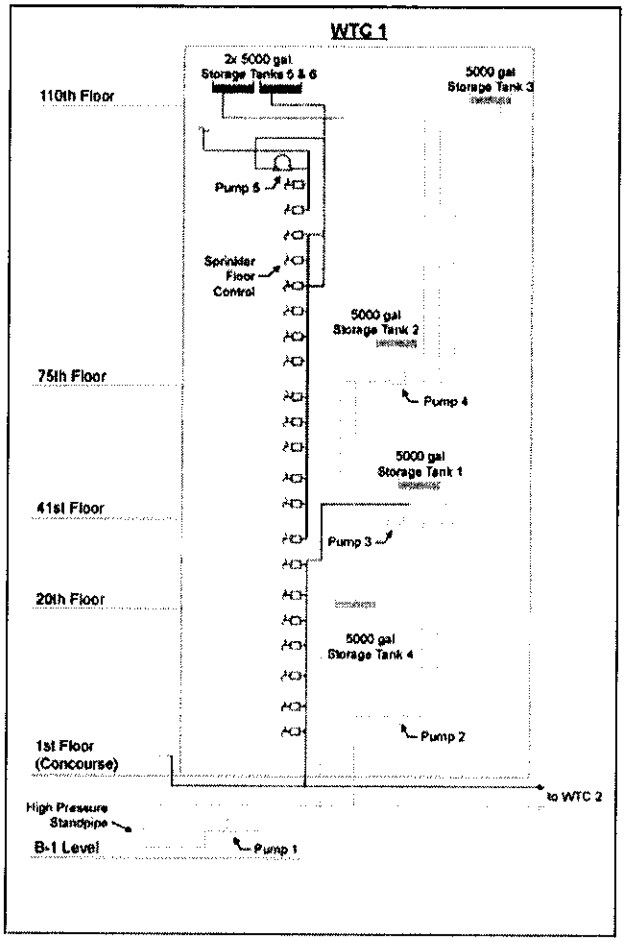


Figure 5–2. Schematic of sprinkler and standpipe systems.

The WTC towers were constructed with a manually activated (by Port Authority staff at the direction of FDNY) smoke purge system, use of which was integrated into The Port Authority's WTC Fire Safety Plan. The system was designed to meet the 1968 NYC Building Code and was functional by September 11, 2001. The non-dedicated system used the existing building ventilation system, in contrast with an alternative dedicated system that would have been used only for smoke management. Each tower was divided into three zones, with the blowers located on the mechanical equipment floors (7, 41, 75, and 108). In the smoke purge mode, the mechanical system was aligned so that an entire zone was vented; there was no provision to vent an individual floor. The smoke from the impact floors in WTC 1 would have been drawn upward to the 108th floor, while the smoke from the impact floors in WTC 2 would have been drawn downward to the 75th floor. The system was designed to clear the zone of smoke after the fire was extinguished, perhaps during post-fire cleanup operations, lest the forced air increase the burning intensity.

5.4 BUILDING INNOVATIONS

5.4.1 The Need for Innovations

Had the towers been built according to conventional design, they would have been heavier and would have had less usable space on each floor. Thus, a resourceful approach was taken in translating The Port Authority's needs and Yamasaki's design into practice.

The Investigation Team identified six innovations incorporated in the lateral-load-resisting system and the gravity-load-carrying system of the towers. Their roles were discussed in Chapter 1. In addition, there were two innovations in achieving the required fire resistance ratings. The innovative, tiered elevator system was also discussed in Chapter 1. The following sections describe these new technologies. The use of sprayed fire-resistive material is discussed in more detail in Section 5.6.

5.4.2 Framed Tube System

WTC 1 and WTC 2 were among the first steel-structure, high-rise buildings built using the framed-tube concept to provide resistance to lateral (wind) loads. The framed-tube system had previously been used in the concrete-framed, 43-story DeWitt-Chestnut and the 38-story Brunswick buildings, both in Chicago and both completed in 1965.

In the framed-tube concept, the exterior frame system resists the force of the wind. The exterior columns carry a portion of the building gravity loads, and in the absence of wind, are all in compression, i.e., the loads push down on and shorten the columns. Under the effect of a strong wind alone, columns on the windward side are in tension, i.e., they elongate as the top of the building bends away from the wind. The columns on the leeward side are compressed. The columns on the walls parallel to the wind are half in tension (on the windward side) and half in compression (on the leeward side). The net effect of combined gravity and wind loads is larger compression on the leeward side and reduced compression, or in rare instances even tension, on the windward side.

Prior to final design, tests had been performed at the University of Western Ontario to assess the stiffness of the wall panels, which consisted of three columns, each three stories high, and the associated spandrel plates as shown in Figure 1–4. These tests used quarter-scale thermoplastic models of panels planned for the 20^{th}, 47^{th}, and 74^{th} floors. (Recall that the structural members became lighter at the higher floors.) The tests also examined the effect of the spandrel thickness, the width of the box columns, and the presence and thickness of stiffeners. Forces were applied to the models, and the resulting deflections measured. The results of these tests guided the final design of the wall panels and provided support for The Port Authority's acceptance of the resulting structural design. This included the innovations described in Sections 5.4.3 and 5.4.4.

5.4.3 Deep Spandrel Plates

The standard approach to construction of the framed tube would have used spandrel beams or girders to connect the columns. The towers used a band of deep plates as spandrel members to tie the perimeter columns together.

5.4.4 Uniform External Column Geometry

In a typical high-rise building, the columns would have been larger near the base of the building and would have become smaller toward the top as they bore less wind and gravity loads. However, the Yamasaki design called for the appearance of tall, uniform columns (Figure 1–2). This was achieved by varying both the strength of the steels and the thickness of the plates that made up the perimeter columns.

5.4.5 Wind Tunnel Test Data to Establish Wind Loads

To determine the extreme wind speeds that could be expected at the top of the towers, Worthington, Skilling, Helle & Jackson (WSHJ) collected data on the wind speeds and directions recorded in the New York area over the prior 50 years. From these data, a design wind speed for the buildings was determined for a 50 year wind event, defined as the wind speed, averaged over a 20 min duration at 1,500 ft above the ground. The estimated value was just under 100 mph in all directions.

To estimate how the buildings would perform under wind loads, both during construction and upon completion, WSHJ conducted a then unique wind tunnel testing program at Colorado State University (CSU) and the National Physical Laboratory (NPL) in the United Kingdom. In each wind tunnel, a physical model of Lower Manhattan, including the towers, was subjected to steady and turbulent winds consistent with the estimated design wind speeds. The model scale was 1/500 for the CSU tests and 1/400 for the NPL tests. The tower models were thus about 3 ft tall. Separate tests were conducted for the single tower and for the two towers at various spacings, with various values of the tower stiffness and damping, and for various wind directions. The two laboratories obtained similar results. Tests on the two-tower models showed that the wind response of each tower was significantly affected by the presence of the other tower.

WSHJ also conducted experiments to determine the wind-induced conditions that would be tolerated by the people who would work in and visit the towers. Breaking new ground in human perception testing, the investigators found that surprisingly low building accelerations caused discomfort.

The test results led to changes in the building design, including stiffer perimeter columns, and the addition of viscoelastic dampers described in the next section. The dampers were used to reduce the building vibrations due to winds.

5.4.6 Viscoelastic Dampers

The tower design included the first application of damping units to supplement the framed-tube in limiting wind-induced oscillations in a tall building. Each tower had about 10,000 dampers.

On most truss-framed floors (tenant floors), a damper connected the lower chord of a truss to a perimeter column. A depiction of the units is shown in Figure 5–3. On beam-framed floors (generally the mechanical floors with their heavier loads), a damper connected the lower flange of a wide-flange beam (that spanned between the core and the perimeter wall) to a spandrel.

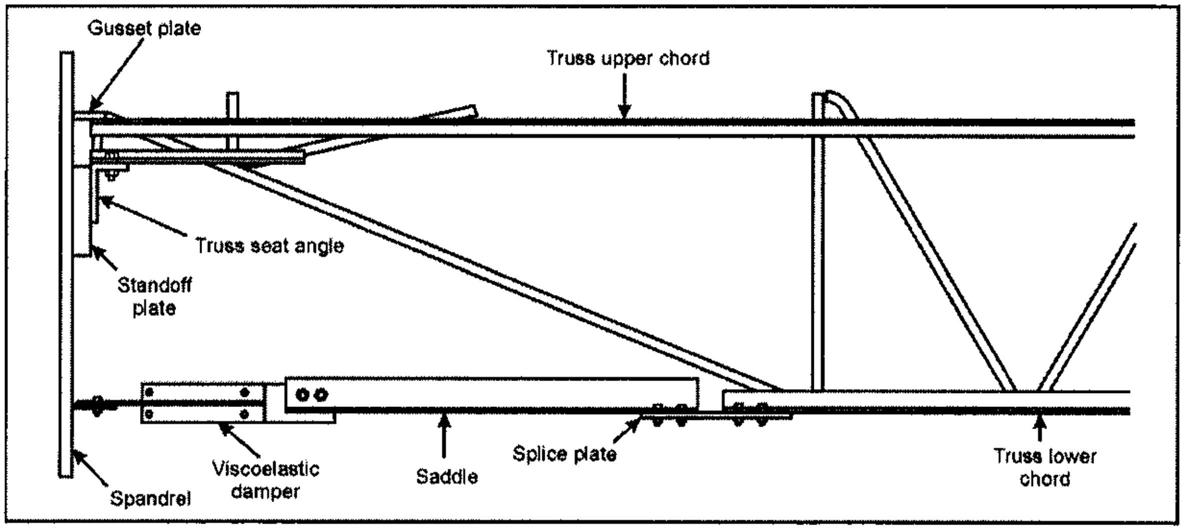


Figure 5–3. Diagram of floor truss showing viscoelastic damper.

Two sets of experiments, conducted by the 3M Company (the manufacturer of the viscoelastic material) and by the Massachusetts Institute of Technology, respectively, examined the damping characteristics of the units. Both studies found that the units provided significant supplemental damping under design conditions.

5.4.7 Long-Span Composite Floor Assemblies

The floor system in the towers (as shown in Figure 1–6) was novel in two respects:

- The use of open-web, lightweight steel trusses topped with a slab of lightweight concrete
- The composite action of the steel and concrete that resulted from the "knuckles" of the truss diagonals extending above the top chord and into the poured concrete

Tests conducted in 1964 by Granco Steel Products and Laclede Steel Company (the manufacturer of the trusses for WTC 1 and WTC 2) determined the effectiveness of the knuckles in providing composite action. Another set of tests, performed by Laclede Steel Company, determined that any failure of the knuckles occurred well beyond the design capacity. A third set of tests, performed at Washington University in 1968, confirmed the prior results and indicated that failure was due to crushing of the concrete near the knuckles.

5.4.8 Vertical Shaft Wall Panels

While similar to other gypsum shaft wall systems and firewalls, the compartmentation system used in the vertical shafts (e.g., for elevators, stairs, utilities and ventilation) was unique in that it eliminated the need for any framing. The walls consisted of gypsum planks placed into metal channels at the floor and ceiling slabs. The planks were 2 in. thick (2½ in. on floors with 16 ft ceiling heights) and 16 in. wide, with metal tongue and groove channels attached to the long sides that served as wall studs. An assembled wall was

then covered with gypsum wallboard. The planks were likely custom fabricated for this job, as the investigators found no mention of similar products in gypsum industry literature of the time or since.

5.5 STRUCTURAL STEELS

5.5.1 Types and Sources

Roughly 200,000 tons of steel were used in the construction of the two WTC towers. The building plans called for an unusually broad array of steel grades and multiple techniques for fabricating the structure from them. The NIST team obtained the information needed to characterize the steels from structural drawings provided by The Port Authority, copies of correspondence during the fabrication stages, steel mill test reports, interviews with fabrication company staff, search of the contemporaneous literature, and measurements of properties at NIST. Sorting through this immense amount of information was made difficult by the large number of fabricators and suppliers, the use of proprietary grades by some of the manufacturers; and the fact that the four fabricators of the impact and fire floor structural elements no longer existed at the time of this Investigation.

Fortunately, the potential for confusion had led the building designers to a tracking system whereby the steel fabricators stamped and/or stenciled each structural element with a unique identifying number. The structural engineering drawings included these identifying numbers as well as the yield strengths of the individual steel components. Thus, when NIST found the identifying number on an element such as a perimeter column panel, the particular steel specified for each component of the element was known, as well as the intended location of the steel in the tower.

In all, 14 grades of steel were specified in the structural engineering plans, having yield strengths from 36 ksi to 100 ksi. Twelve were actually used, as the fabricators were permitted to substitute 100 ksi steel where yield strengths of 85 ksi and 90 ksi were specified. Table 5–1 indicates the elements for which the various grades were used. The higher yield strength steels were used to limit building weight while providing adequate load-carrying capacity.

Table 5–1. Specified steel grades for various applications.

Application	Yield Strength (ksi)											
	36	42	45	46	50	55	60	65	70	75	80	100
Perimeter columns	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Spandrel plates	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Core columns	✓	✓	(a)		(a)							
Floor trusses	✓				✓							

a. About 1 percent of the wide flange core columns were specified to be of these higher grades.

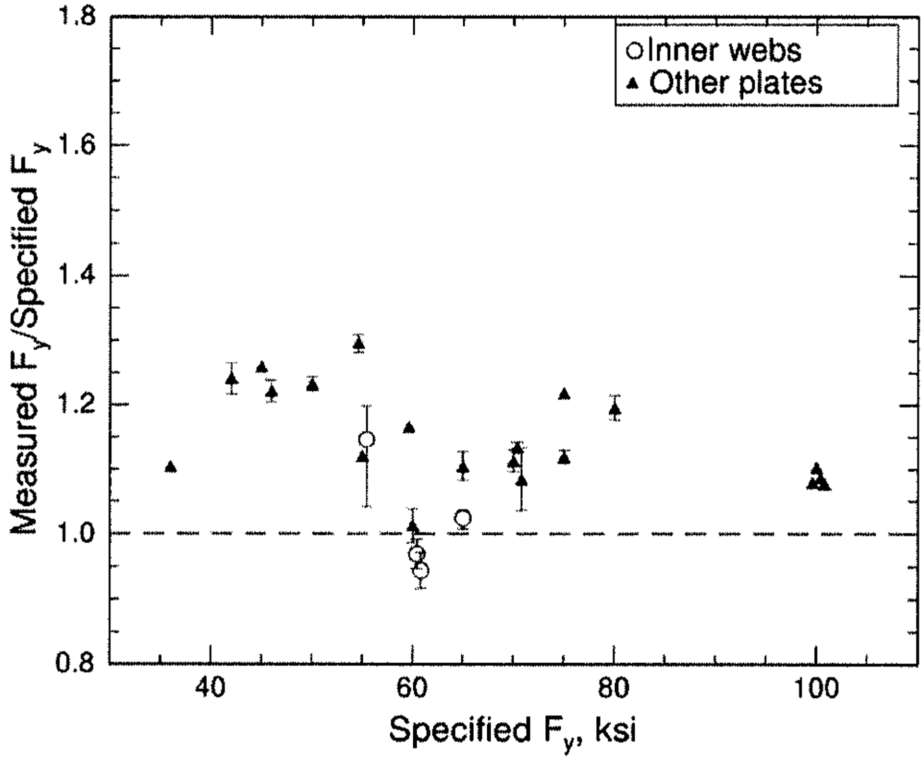
5.5.2 Properties

The Port Authority required a thorough and detailed quality assurance programs to ensure compliance with the specifications for the steel, welds, and bolts. The steel data went beyond the minimum yield strength (the property of greatest importance) to include tensile strength and ductility. The quality assurance program included unannounced inspections and confirming tests.

NIST performed confirmatory tests on samples of the 236 pieces of recovered steel to determine if the steel met the structural specifications. Making a definitive assessment was complicated by overlapping specifications from multiple suppliers, differences between the NIST test procedures and the test procedures that originally qualified the steel, the natural variability of steel properties, and damage to the steel from the collapse of the WTC towers. Nonetheless, the NIST investigators were able to determine the following:

- There were 14 grades (strengths) of steel that were specified. However, a total of 32 steels in the impact and fire floors were sufficiently different (grade, supplier, and gage) to require distinct models of mechanical properties.
- The steels in the perimeter columns met their intended specifications for chemistry, mechanical properties, yield strengths, and tensile properties. The steels in the core columns generally met their intended specifications for both chemical and mechanical properties.
- Roughly 13 percent of the measured strength values for the perimeter and core columns were at or below the specified minimums (Figure 5–4). The strength variation was consistent with the historical variability of steel strength and with the effects from damage during the collapse of the towers. The measured values were within the typical design factor of safety.
- The yield strengths of many of the steels in the floor trusses were above 50 ksi, even when they were specified to be 36 ksi.
- Tests on a limited number of recovered bolts showed they were much stronger than expected based on reports from the contemporaneous literature.

The mechanical properties of steel are reduced at elevated temperatures. Based on measurements and examination of published data, NIST determined that a single representation of the elevated temperature effects on steel mechanical properties could be used for all WTC steels. Separate values were used for the yield and tensile strength reduction factors for bolt steels.



Note: The ratio values less than 1 arose from natural variation in the steel and did not affect the safety of the towers on September 11, 2001. The bars represent maximum and minimum values from multiple measurements.

Figure 5–4. Ratio of measured yield strength (F_y) to specified minimum yield strength for steels used in WTC perimeter columns.

5.6 FIRE PROTECTION OF STRUCTURAL STEEL

5.6.1 Thermal Insulation

When steel is heated it loses both strength and stiffness. Thus, measures must be taken to protect the steel in a structure from temperature rise (and consequent loss of strength) in case of fire.

Bare structural steel components can heat quickly when exposed to a fire of even moderate intensity. Therefore, some sort of thermal protection, or insulation, is necessary. This insulation can be in direct contact with the steel, such as a sprayed fire-resistive material (SFRM), or can be a fire resistant enclosure surrounding a structural element.

5.6.2 Use of Insulation in the WTC Towers

The thermal protection of the steel structures in the WTC towers included a combination of SFRM and enclosures of gypsum wallboard. The use of SFRM for floor truss protection was new in high-rise buildings, and the requirements evolved during the construction and life of the towers. By examining documents supplied by The Port Authority, LERA, and the SFRM manufacturers, NIST was able to

document much of the sequence of these changing requirements and arrive at an estimation of the passive protection in place on September 11, 2001.

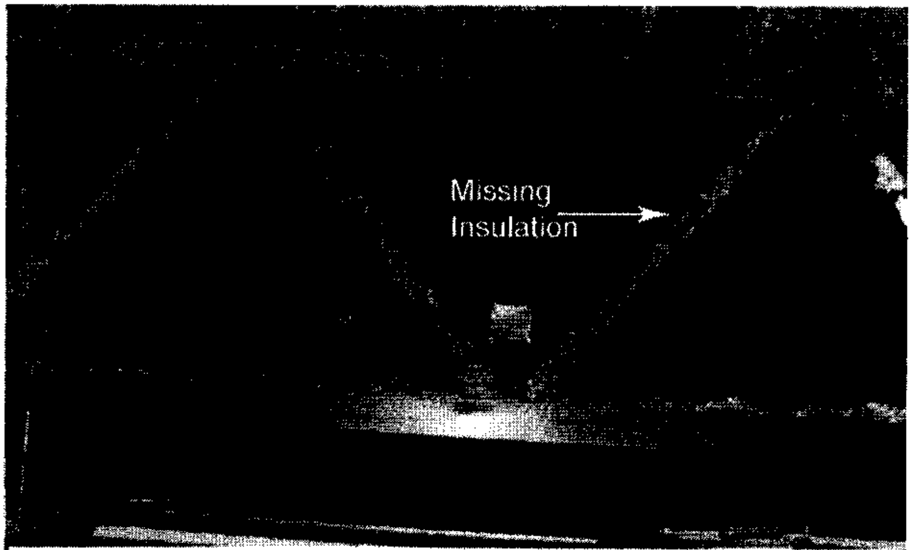
Floor Systems

At the time the WTC was designed, the ASTM E 119 test method had been used for nearly 50 years to determine the fire resistance of structural members and assemblies. However, The Port Authority confirmed to the Investigation Team that there was no record of fire endurance testing of the innovative assemblies representing the thermally protected floor system used in the towers. The floor assembly was not tested despite the fact that the Architect of Record and the Structural Engineer of Record stated that the fire rating of this novel floor system could not be determined without testing.

Prior to construction, the Architect of Record had used information from (unidentified) manufacturers to recommend a 1 in. thickness of SFRM around the top and bottom chords of the trusses and a 2 in. thickness for the web members of the trusses. This was to achieve the fire endurance requirements for Class 1A construction (Section 5.3.3).

In 1969, The Port Authority directed that a ½ in. thick coating of BLAZE-SHIELD Type D (BLAZE-SHIELD D), a mixture of cement and asbestos fibers, be used to insulate the floor trusses. This was to achieve a Class 1A rating, even though the preponderance of evidence suggests that the towers were chosen to be Class 1B, the minimum required by the NYC Building Code. NIST found no evidence of a technical basis for selection of the ½ in. thickness. This coating had been installed as high as the 38th floor of WTC 1 when its use was discontinued due to recognition of adverse health effects from inhalation of asbestos fibers. The spraying then proceeded with BLAZE-SHIELD DC/F, a similar product in which the asbestos was replaced by a glassy mineral fiber and whose insulating value was reported by Underwriters Laboratories, Inc., to be slightly better than that of BLAZE-SHIELD D. On the lower floors, the BLAZE-SHIELD D was encapsulated with a sprayed material that provided a hard coat to mitigate the dispersion of asbestos fibers into the air.

In 1994, The Port Authority measured the SFRM thickness on trusses on floors 23 and 24 of WTC 1. In all, average thicknesses were reported for 32 locations, and the overall average thickness was found to be 0.74 in. NIST performed a further evaluation of the SFRM thickness using photographs taken in the 1990s of floor trusses on (non-upgraded) floors 22, 23, and 27 of WTC 1 (Figure 5–5). By measuring dimensions on the photographs, NIST estimated the insulation thicknesses on the diagonal web members of trusses. (The thickness of chord member insulation could not be measured.) The average thickness and standard deviation of web members was 0.6 in. ± 0.3 in. on the main trusses, 0.4 in. ± 0.25 in. on the bridging trusses, and 0.4 in. ± 0.2 in. on the diagonal struts. These numbers indicated that there were areas where the coating thickness was less than the specified 0.5 in.



Note: Enhancement by NIST.

Figure 5–5. Irregularity of coating thickness and gaps in coverage on SFRM–coated bridging trusses.

In 1995, The Port Authority performed a study to establish requirements for retrofit of sprayed insulation to the floor trusses during major alterations when tenants vacated spaces in the towers. Based on design information for fire ratings of a similar, but not identical, composite floor truss system contained in the Fire Resistance Directory published by Underwriters Laboratories, Inc., the study concluded that a 1½ in. thickness of sprayed mineral fiber material would provide a 2 hour fire rating, consistent with the Class 1B requirements. In 1999, the removal of existing SFRM and the application of new material to this thickness became Port Authority policy for full floors undergoing new construction and renovation. For tenant spaces in which only part of a floor was being modified, the SFRM needed only to be patched to ¾ in. thickness or to match the 1½ in. thickness, if it had previously been upgraded. In the years between 1995 and 2001, thermal protection was upgraded on 18 floors of WTC 1, including those on which the major fires occurred on September 11, 2001, and 13 floors of WTC 2 that did not include the fire floors. The Port Authority reported that the insulation used in the renovations was BLAZE-SHIELD II.

In July 2000, an engineering consultant to The Port Authority issued a report on the requirements of the fire resistance of the floor system of the towers. Based on calculations and risk assessment, the consultant concluded that the structural design had sufficient inherent fire performance to ensure that the fire condition was never the critical condition with respect to loading allowances. The report recommended that a 1.3 in. thickness be used for the floor trusses.

In December 2000, another condition assessment concluded that the structural insulation in the towers had an adequate 1 hour rating, considering that all floors were now fitted with sprinklers. The report also noted the ongoing Port Authority program to upgrade the fire-resistive material thickness to 1½ in. in order to achieve a 2 hour fire rating.

The Port Authority provided NIST with the records of measurements of SFRM thickness on upgraded floors in both towers. The average thickness and standard deviation on the main trusses was 2.5 in. ± 0.6 in., based on 18 data sets with a total of 256 measurements. NIST analysis of several Port Authority photographs from the 1990s of the upgraded 31st floor of WTC 1 indicated an average thickness and standard deviation on the main trusses of 1.7 in. ± 0.4 in., based on 52 measurements from five web members in two photographs. NIST gave more weight to the measured data, which were taken according to a standard procedure in ASTM E 605, than to the data scaled from photographs, for which there was neither standard procedure nor calibration of the method.

Perimeter Columns

In 1966, the contractor responsible for insulating the perimeter columns proposed applying a 1 3/16 in. thick coating of BLAZE-SHIELD D to the three external faces (Figure 5–6) to achieve a 4 hour rating, which is a Class 1A rating requirement (1 hour more than Class 1B). NIST found evidence of a technical basis for this decision. In the construction drawings prepared by the exterior cladding contractor, the following SFRM thicknesses were specified:

- 7/8 in. of vermiculite plaster on the interior face and 1 3/16 in. of BLAZE-SHIELD D on the other three faces.
- ½ in. of vermiculite plaster on the interior surfaces of the spandrels and ½ in. of BLAZE-SHIELD D on the exterior surfaces.

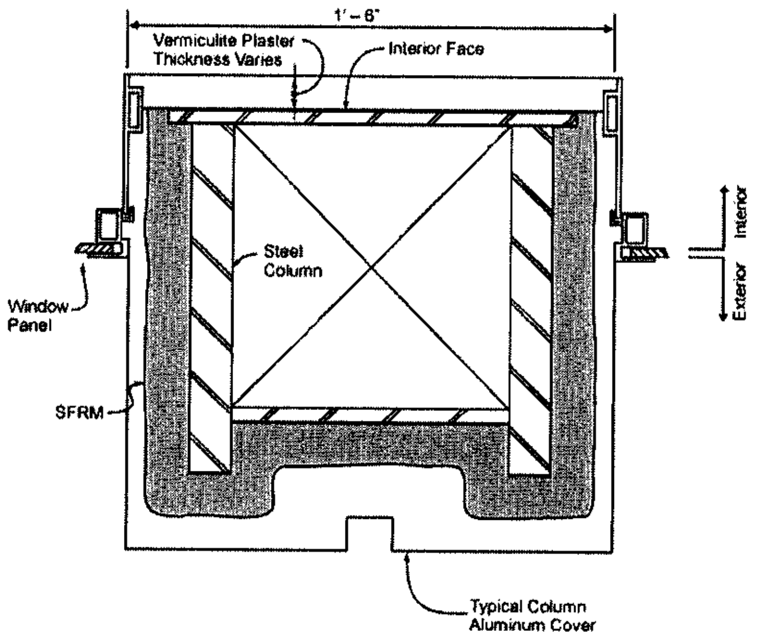


Figure 5–6. Thermal insulation for perimeter columns.

Vermiculite plaster had a higher thermal conductivity and thereby increased heat migration from the room air to the column steel and, thus, could keep the steel temperature at 70 °F when the temperature was 0 °F outside.

In October 1969, The Port Authority provided the following instructions to the contractor applying the sprayed fire protection, in order to maintain the Class 1-A Fire Rating of the NYC Building Code:

- 2 3/16 in. of BLAZE-SHIELD D for columns smaller than 14WF228[12] and 1 3/16 in. for columns equal to or greater than 14WF228.

- ½ in. covering of BLAZE-SHIELD D for beams, spandrels and bar joists.

NIST's review of available documents has not uncovered the reasons for selecting BLAZE-SHIELD fire-resistive material or the technical basis for specifying ½ in. thickness of SFRM for the floor trusses. As with the trusses, BLAZE-SHIELD DC/F was applied to the perimeter columns above the 38th floor of WTC 1 and all the perimeter columns in WTC 2.

Core Columns and Beams

Multiple approaches were used to insulate structural elements in the core:

- Those core columns located in rentable and public spaces, closets, and mechanical shafts were enclosed in boxes of gypsum wallboard (and thus were inaccessible for inspection). The amount of the gypsum enclosure in contact with the column varied depending on the location of the column within the core. SFRM (BLAZE-SHIELD D and DC/F) was applied on those faces that were not protected by the gypsum enclosure. The thicknesses specified in the construction documents were 1 3/16 in. for the heavier columns and 2 3/16 in. for the lighter columns.

- Columns located at the elevator shafts were protected using the same SFRM thicknesses. They were not enclosed and thus were accessible for routine inspections.

Inspection of the columns within the elevator shaft spaces in 1993 indicated some loss of SFRM coverage. As a result, new insulation was applied to selected columns within the elevator shaft space. Information provided to NIST indicated that a different SFRM, Monokote Type 2-106, was used. Thickness measurements for columns and beams below the 45th floor indicated average thicknesses of 0.82 in. and 0.97 in., respectively. Information from The Port Authority indicated that the minimum required thickness of the re-applied SFRM was ½ in. for the columns and ¾ in. for the beams.

NIST was unable to locate information from which to characterize the insulation of the core columns and beams that were not accessible. Except as noted above, once completed, the core was generally not inspected. NIST was not able to locate any post-collapse core beams or columns with sufficient insulation still attached to make pre-collapse thickness measurements.

Summary of SFRM on September 11, 2001

Table 5–2 summarizes the types and thicknesses of the SFRMs used in the towers. According to Port Authority documents, in the upper part of the towers, trusses on floors 92 through 100 and 102 in WTC 1

[12] This designation indicates that the column is a 14 in. deep wide flange section and weighs 228 pounds per foot.

had upgraded insulation by September 11, 2001. In WTC 2, truss insulation had been upgraded on floors 77, 78, 85, 88, 89, 92, 96, 97, and 99.

Table 5–2. Types and locations of SFRM on fire floors.

Building Component	Material	Thickness (in.)		
		Specified[a]	Installed	Used in Analysis[b]
FLOOR SYSTEM				
Original				
Main trusses and diagonal struts	BLAZE-SHIELD DC/F	0.5	0.75	0.6
Bridging trusses (one-way zone)[c]	BLAZE-SHIELD DC/F	0.5	0.38[d]	0.3
Bridging trusses (two-way zone)[c]	BLAZE-SHIELD DC/F	0.5	0.38[d]	0.6
Upgraded				
Main trusses	BLAZE-SHIELD II	1.5	2.5	2.2
Main truss diagonal struts	BLAZE-SHIELD II	1.5	2.5	2.2
Bridging trusses	BLAZE-SHIELD II	1.5	2.5	2.2
EXTERIOR WALL PANEL				
Box columns				
Exterior face	BLAZE-SHIELD DC/F	1 3/16	(e)	1.2
Interior face	Vermiculite plaster	7/8	(e)	0.8
Spandrels				
Exterior face	BLAZE-SHIELD DC/F	0.5	(e)	0.5
Interior face	Vermiculite plaster	0.5	(e)	0.5
CORE COLUMNS				
Wide flange columns				
Light	BLAZE-SHIELD DC/F	2 3/16	(e)	2.2
Heavy	BLAZE-SHIELD DC/F	1 3/16	(e)	1.2
Box columns				
Light	BLAZE-SHIELD DC/F	(f)	(e)	2.2[(g)]
Heavy	BLAZE-SHIELD DC/F	(f)	(e)	1.2[(g)]
CORE BEAMS	BLAZE-SHIELD DC/F	0.5	(e)	0.5

a. "Specified" means material and thicknesses determined from correspondence among various parties.
b. The analysis is described in Chapter 6.
c. Not expressly specified. SFRM was required for the areas where the main trusses ran in both directions and, while not required, was also applied in the areas where they ran in one direction only.
d. Analysis of photographs indicated that the thickness was approximately one half that on the main trusses.
e. Not able to determine.
f. Not specified.
g. Thickness assumed equal to wide flange columns of comparable weight per foot.

5.7 CONCRETE

Two types of concrete were used for the floors of the WTC towers: lightweight concrete in the tenant office areas and normal weight concrete in the core area. Because of differences in composition and weight, the two types of concrete respond differently to elevated temperatures, as shown in Figure 5–7. While their tensile strengths degrade identically, lightweight concrete retains more of its compressive strength at higher temperatures. The degradation of concrete mechanical properties with temperature was included in the structural response analysis of the floor systems.

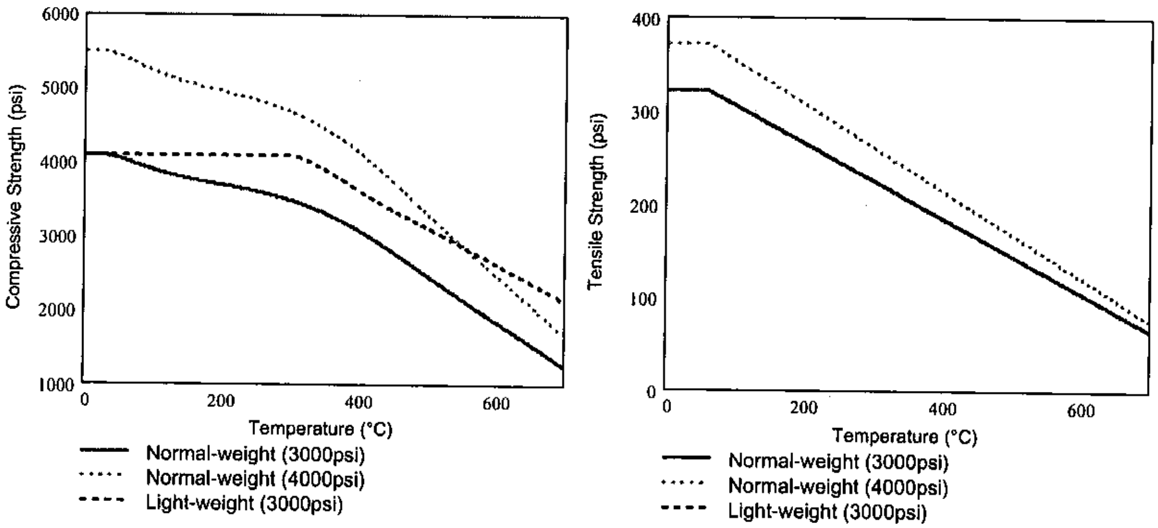


Figure 5–7. Temperature–dependent concrete properties.

5.8 THE TENANT SPACES

5.8.1 General

About 80 percent of the floors had a single tenant. Many of these floors were filled with arrays of modular office cubicles, their low partitions affording sightlines to the windows, with perhaps an occasional perimeter conference room or executive office in the way (Figure 1–11). Trading floors (Figure 1–12) had tables and computers throughout and food service areas to minimize time away from the non-stop transactions. The remaining 20 percent of the floors were each subdivided among as many as 25 tenants. Some of the approximately 25 tenants that occupied two or more contiguous floors installed convenience stairways within their own space.

Certain floors were of special interest to the Investigation. These were the floors on which there was structural damage from the aircraft and/or on which extensive fires were observed. These floors, designated as focus floors, and the information NIST obtained regarding them are characterized in Table 5–3. Additional information, obtained from the tenant firms and The Port Authority, is summarized in the remainder of this chapter.